SYMPOSIUM Y

Solid Freeform and Additive Fabrication III

April 24 – 26, 2000

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Symposium Support
Office of Naval Research
Sandia National Laboratories

Proceedings published as Volume 625
of the Materials Research Society
Symposium Proceedings Series.

*Invited paper
SESSION Y1: DIRECT METAL FABRICATION
Chairs: Paul F. Jacobs and Fritz B. Prinz
Monday Morning, April 20, 2006
Salon 13 (Marriott)

8:30 AM Y1.1
FABRICATION OF Ti-Al ALLOYS FROM ELEMENTAL POWDER:
BLENDS WITH THE LENS™ TECHNOLOGY, Karin L.
Schwendner and Hamish L. Frazer, Dept. of Materials Science
and Engineering, The Ohio State University, Columbus, OH.

Unlike conventional metalworking technologies, the LENS™ process builds components in an additive manner. It is a direct material fabrication process in which a fully dense part can be formed. In the process, a Nd:YAG laser is used to melt and solidify elemental powder into a net-shape component. To build parts from complex alloys such as Ti-Al alloys, powders with the desired composition have to be consolidated first. Generally, the fabrication of these pre-alloyed powders is cost-intensive. Therefore, the use of elemental powders has been investigated. Samples with the following compositions have been deposited using elemental powder blends: Ti-10%Nb, Ti-10%Cr and Ti-8%Al-2%Cr-2%Nb. The influence of the various factors affecting the quality of these deposits will be discussed. The elemental blend deposits of Ti-8%Al-2%Cr-2%Nb have been compared with deposits made of pure powders. The deposit microstructures have been characterized using SEM and TEM techniques, and the role of microstructure will be discussed. After the deposition the Ti-8%Al-2%Cr-2%Nb deposits show evidence of cracking. To avoid this stress relief heat treatments as well as the heating of the substrate prior to deposition have been investigated.

8:45 AM Y1.2
HEAT TREATMENT, MICROGRAPHIC EXAMINATION, AND THERMAL MODELING OF LASER FORMED Ti-6Al-4V,
S.M. Kelly, S. Signorini, Virginia Tech Alexandria Research
Depts, Blacksburg, VA; C.R. Croke, Virginia Tech Alexandria
Research Inst., Alexandria, VA; R.T. Shattey, Boeing/Phantom Works, St. Louis, MO.

Ti-6Al-4V structural parts have been formed using a laser direct metal deposition process, known as laser forming. The laser forming process combines high power laser channelling technologies, with the advanced methods and rapid prototyping to manufacture complex, near-net-shape metal parts. A large information base exists for heat treatments of forged and cast Ti-6Al-4V; however, there is presently not much information available on the heat treatments of laser formed Ti-6Al-4V. The work to be discussed is an investigation of the effect of heat treatment and cooling rates on the microstructure of bulk laser formed Ti-6Al-4V. The current results of a finite element model of the laser forming process will also be presented. The model will be used to refine the laser forming cooling rate and the observed microstructure of the as-formed samples with the cooling rate and microstructure obtained by conventional heat treatments. The above research is sponsored by the Office of Naval Research.

9:00 AM Y1.3
UNDERSTANDING THE MICROSTRUCTURE AND PROPERTIES OF COMPONENTS FABRICATED BY LASER ENGINEERED NET

Solid freeform fabrication is one of the fastest growing automated manufacturing technologies that has significantly impacted the length of time between initial concept and actual part fabrication. This talk will describe recent developments in a new technology, known as LENS (Laser Engineered Net Shaping), to fabricate metal components directly from CAD solid models. In a manner analogous to stereolithography or selective sintering, the LENS process builds metal parts line by line and the use of layer-by-layer, powder particles are injected into a laser beam, where they are melted and deposited onto a substrate as a miniature weld pool. The trace of the laser beam on the substrate is driven by the definition of CAD models. Once the net-shape density and shape has been achieved, the microstructure of the component is highly dependent on the processing parameters (laser power, scan velocity, powder feed rate) and the temperature history of the component. In this talk, we will present results of our efforts to determine the processing parameters that could be predicted and controlled when using the LENS process. Finally, we will show applications of the technology.

This work supported by the U.S. Dept of Energy under contract DE-AC04-94AL85000. Sandia National Laboratories is a multiprogram lab operated by Sandia Corp., a Lockheed Martin Co., for the U.S. Dept of Energy.

9:30 AM Y1.4
CHANGE IN MICROSTRUCTURE AND MECHANICAL PROPERTIES OF STAINLESS STEEL 314S DURING SELECTIVE
LASER SINTERING, Carl Hasager, T.H.C. Childs, K.W. Dalogreno,
R.B. Easte, School of Mechanical Engineering, The University of Leeds, UNITED KINGDOM.

Four batches of stainless steel 314S powder with particle size fractions of 30-45, 45-65, 65-100, and 100-150 μm were subjected to selective laser sintering (SLS) within an argon atmosphere using a CO2 laser. Both single line passes and single layers were sintered then sectioned and prepared for metallographic inspection. Microstructural observations showed that increases in net heat input into the powder enlarged the melt volume fraction under the travelling laser beam causing grain coarsening and a change from the originally dendritic microstructure to a more prominent columnar microstructure. Mechanical tests were also carried out revealing property homogenization of single layers as laser power increased and scan speed and scan spacing decreased. This paper maps the variations in microstructure and physical properties as sintering conditions change and highlights observations of melt pool quality variation within these conditions.

9:45 AM Y1.5
MICROSTRUCTURE AND PROPERTIES OF LASER DEPOSITED 304L AUSTENITIC STAINLESS STEEL, J.A. Brooks, C.V.

The use of laser deposition of powders to build three-dimensional structures is in many ways similar to a number of welding processes. It is well known that the solidification behavior and microstructures of 304L welds are highly dependent upon weld process and alloy composition. A wide range of microstructures from single-phase austenite to ferrite-austenite two-phase structures can be achieved. The goal of this work is to determine to what extent laser-deposited austenitic microstructures could be obtained through the manipulation of composition, solidification mode, and solid state transformations. Samples of four different alloy compositions were deposited over a range of processing parameters that could yield single-phase microstructures. Microstructures of deposits were characterized using both optical and electron microscopy techniques and compared to those obtained during high energy density welding and to microstructural predictions. Tensile properties of the laser deposited structures will also be reported. This work was funded by the United States Department of Energy under contract #DE-AC04-94AL85000.

10:00 AM Y1.6
A COMPARISON OF RESIDUAL STRESS CONTROL ISSUES FOR THERMAL DEPOSITION OF POLYMERS AND METALS IN SFF
PROCESSING: Jack Reut, Robert Ong, Center for<br>Depts of Mechanical Engineering, Pittsburgh, PA; Nathan Klingebl, Wright State Univ., Dept. of Mechanical & Materials Engineering, Dayton, OH; Lee Weiss, Carnegie Mellon Univ., Robotics Institute, Pittsburgh, PA.

Residual stress-induced failure in structures is a significant concern in the use of laser sintering for rapid prototyping. In particular, stress-induced cracking and warping are of major concern in the use of rapid prototyping and casting technology. In this research, warping experiments and residual stress models are used to compare how residual stresses evolve in the building of metal and polymeric parts by thermal deposition-based SFF processes. Specifically, results for deposition of 304 stainless steel via a laser-based method and 3D printing of ABS product, using two different deposition methods. Different deposition methods are used in conjunction with CNC machining in the Shape Deposition Manufacturing process. Issues considered include the depth to which stress is induced in existing material layers, the role of induced heating by the process in reducing residual stresses, and the importance of high-temperature properties of determining final residual stress magnitudes and the directionality of warping for a given material deposition path. Each of these issues is considered with regard to strategies for reducing residual stress magnitudes (and warping) for both types of material systems.

10:45 AM Y1.7
NOVEL MICROSTRUCTURES BY DIRECT METAL DEPO-
SION, Katherine C. Chen, California Polytechnic State University, Materials Engineering Dept., San Luis Obispo, CA; Dan J. Thoma, Los Alamos National Laboratory, Los Alamos, NM.

With the advance of solid freeform fabrication techniques, truly
unique microstructures can be tailored for enhanced properties. Direct metal deposition allows rapidly solidified bulk samples to be produced in the near-net-shape form. With cooling rates up to $10^5$ K/s, metastable phases become possible. Microstructure formation at the liquid/solid interface indicate that interface equilibrium conditions are not necessarily adhered. Characterization of the rapid solidification phenomena and the implications related to properties of the fabricated materials will be discussed. Furthermore, systematic investigations of processing parameters are coupled with solidification modeling efforts in an attempt to understand processing structure-properties relationships of various materials. For instance, doubling of the laser traverse speed results in the reduction of the primary dendrite arm spacings by 15% in the Fe-25Ni model system. As a consequence, ultimate tensile strength and ductility increase in eutectic systems, direct metal deposition is employed to vary eutectic spacings, as well as, to control the growth direction with subsequent phases during fabrication. Length scales and connectivity of individual phases in multiphase alloys are thus somewhat controlled and unique properties result. Such design of micro-structures for optimized properties is unattainable with conventional processing techniques.

11:00 AM Y18
CHARACTERIZATION OF LASER DEPOSITED NIOMIUM AND MOLYBDENUM SILICIDES: C.A. Brice, J.I. Schwindler, S. Amoscheria, H.I. Fraser, The Ohio State University, Department of Materials Science and Engineering, Columbus, OH; X.D. Zhang, Reynolds Aluminum Company, Richmond, VA.

Recent advances in solid freeform fabrication techniques have opened the door to new methods for producing materials that are difficult to process by conventional means. Molybdenum and niobium silicides have the potential for high temperature structural applications, however, their low melting temperatures have hindered their practical use. Introducing a continuous second phase can greatly enhance the mechanical properties of these materials at low temperatures. This paper describes a method of in-situ alloying of molybdenum and niobium silicides using the LENS (Laser Engineered Net Shaping) process. Elemental blends of niobium/silicon and molybdenum/silicon/carbon were laser deposited and the resultant microstructures were evaluated by various analytical techniques. The results show that a homogeneous in-situ composite can be produced where the silicide phases are toughened by a continuous eutectic phase.

11:15 AM Y19
PROCESS MAPS FOR BUILDING THIN-WALLED STRUCTURES BY LASER-BASED SFF PROCESSES: Jack Beach, Atul Vaidyanath, Carnegie Mellon Univ., Dept. of Mechanical Engineering, Pittsburgh, PA; Michelle Griffith, Sandia National Laboratories, Albuquerque, NM.

In solid freeform fabrication (SFF) processes involving thermal deposition, thermal control of the process is critical for obtaining consistent deposition conditions and in limiting residual stress-induced warping of parts. In this research, two-dimensionalized plots (termed process maps) are developed from empirical models of laser-induced stress behavior. In addition, suitable stress relief techniques are developed to mitigate the effects of changes in laser power, deposition speed and part preheating on melt pool size and residual stress magnitudes. The principal application of this work is to the Laser Engineered Net Shaping (LENS) process under development at Sandia National Laboratories; however, the approach taken is applicable to any solid freeform fabrication process involving a laser or other moving heat source. Process maps are being developed in parallel with thermal imaging experiments as a means for checking the numerical predictions of melt pool size and for identifying key experiments to be performed. The results of this research will provide a better understanding of the interactions between process parameters and could serve as the basis for an automated process control system.

11:30 AM Y20
INVESTIGATION INTO FREEFORM FABRICATION OF MULTIMATERIAL PARTS BY 3D WELDING AND MILLING PROCESS: Yong-Ak Song, Sehyung Pak, Korea Institute of Science and Technology KIST, CAD/CAM Center, Seoul, KOREA.

3D Welding and Milling developed at Korea Institute of Science and Technology KIST combines the conventional welding and milling process to exploit the advantages of both processes. On the one hand, the additive method gives the possibility to create features which have been impossible to manufacture so far such as internal channels and multi-material systems. On the other side, the machining process gives a high accuracy and surface quality. In this paper, freeform fabrication of parts using two different materials during deposition is experimentally investigated. When depositing a layer, a conventional mild steel is used to fill the area and a different type of steel such as stainless steel is used to fill the boundary area. In this way, a part is created which consists of a soft material inside and a material of different characteristics on the outside. The method of using different materials can be also extremely useful when building conformal cooling channels. Copper or bronze can be applied around the channel to increase the thermal conductivity of steel molds. The results of using two different materials in freeform fabrication and the process problems such as different thermal expansion are discussed in the paper.

SESSION Y3: TOOLING AND PHOTO PROCESSING
Chair: Jack L. Beach and Michelle L. Griffith
Monday Afternoon, April 24, 2000
Salon 13 (Marriott)

1:30 PM Y2.1
DIMENSIONALLY ACCURATE MOLD INSERTS AND METAL COMPONENTS BY DIRECT METAL LASER SINTERING: Jan-Erik Land, Juha Karttula, Tatu Syvans, Olli Nyhart, Rapid Product Innovations Oy, Raisio, FINLAND.

One of the main shortcomings in the current rapid tooling techniques is the capability of producing only near-net-shape parts. Direct Metal Laser Sintering (DMLS) is a technique that enables the fabrication of true net-shape parts in just a few hours and with only minimum post-processing. DMLS is a laser-based rapid tooling process developed in Europe by ElectroLaser Rapid Development Finland and EDAG GmbH, Germany. ElectroLaser Rapid Development was also the first to implement this technology to functional prototyping by using two proprietary bronze-based powders and a new steel-based powder. The technique enables the fabrication of tailored microstructures from porous parts to near full density. Thus, functionally gradient structures can be fabricated, i.e. material is sintered to full density only where it is needed. This paper describes the philosophy of fabricating true net-shape mold inserts and metal components, but also concentrates on how to maintain the dimensional accuracy even after the post-processing. The study shows that even +/- 0.05 mm accuracy can be obtained. The results of the study also illustrate the beneficial effects of reduced layer thickness and post-processing on the surface roughness and mechanical properties as well as the suitability of various conventional and non-conventional coatings. With reduced layer thickness, the step-shaped effect of the layers was no longer visible. The surface was even further improved by shot peening and coating. In addition, case studies from injection molding, pressure die-casting and direct metal component fabrication are presented.

1:45 PM Y2.2
ADVANCED MOLD DESIGN USING ADDITIVE FABRICATION: Paul F. Jacobs, Laser Fab Advanced Technology Group, Warwick, RI.

This paper will discuss recent developments involving the use of additive fabrication techniques in the design, development and fabrication of advanced core and cavity inserts currently being used in actual production injection molding applications. Starting with a CAD model of the part, one develops a CAD model of the tool, and then generates CNC cutters to machine the finished mold. The active mold surface is developed in an additive process involving electroforming nickel directly onto the mandrel. After a sufficient thickness of nickel has been added to ensure long tool life, the assembly is removed from the nickel vat and placed in a copper electroforming vat. A copper thermal management layer is then also fabricated through additive techniques. The electroformed copper layer is built on it to provide conformal cooling channels. Finally, the inserts are machined with steel, fitted with ejector pins, and secured in a steel mold frame. Finite element analysis mold temperature distributions will be shown for conventional machined steel inserts. These will be compared with temperature distributions for the new electroformed nickel-copper inserts backed with steel. Specifically, data will be presented regarding: (1) the use of high thermal conductivity mold materials, (2) the influence of conformal cooling channels, (3) active mold surface temperature distributions during injection molding, and (4) reductions in mold cycle time.

2:15 PM Y2.3
CONFORMABLE COOLING VS. CONVENTIONAL COOLING: AN INJECTION MOLDING CASE STUDY WITH 3-DIMENSIONAL PRINTING: Wayne R. Schmidt, Ronald D. White*, Connie E. Bird and Joseph V. Bink, United Technologies Research Center, East Hartford, CT; GE Appliances, Louisville, KY.

A series of designed experiments was performed in an attempt to quantify the historically "mysterious" benefits of conformal cooling for injection molding tooling. The experiments considered different cavity part geometries, gating schemes, mold materials and cooling approaches. This presentation will provide an overview of the mold design
approach, cooling simulation, tool fabrication via the 3D Printing(TM) process, as well as part molding and inspection results.

2:30 PM Y#2.4
RAPID ELECTROFORMING TOOLING. Bo Yang, New Jersey Institute of Technology, Department of Mechanical Engineering, Newark, NJ; Ming C. Leu, University of Missouri-Rolla, Department of Mechanical and Aerospace Engineering and Engineering Mechanics, Rolla, MO.

This paper presents an analytical and experimental study of a relatively new rapid tooling process called the Rapid Electroforming Tooling (REIT) process. This process integrates solid freeform fabrication (SFF) with electroforming to produce molds, dies, and electronic devices. Electroforming (EDM) geometry rapidly and accurately. The basic process steps involved in REIT are as follows. An SFF part is built and metalized for electroforming. The part is then placed in an electroplating solution and metal is deposited upon the part by electroplating. When the densified thickness of metal has been deposited, the SFF part is separated from the metal shell, and the shell is backfilled with other materials to form a mold cavity or an EDM electrode. A nickel electroform can be used for a prototyping mold or even a production mold, and a copper electroform can be used as an EDM electrode. Thermomechanical finite element analysis implemented in ANSYS software was used to predict the thermal stresses generated during the burnout process, which removes a stereolithography pattern from the electroform. The thermal stress analysis was performed for stereolithography patterns of two- and three-dimensional geometry and varying electroform thickness. An experiment was conducted using strain gauges to measure the thermal stress generated during the burnout process. The results of an experiment agree well with the predicted thermal stresses.

3:30 PM Y#2.5
DMD PROCESS PROVIDES UNIQUE MICROSTRUCTURES FOR IMPROVED STRENGTH AND DIE LIFE. ABILITY TO CREATE SMART PARTS. Dwight M. Morgan, Precision Optical Manufacturing Company, Plymouth, MI.

This presentation will review the benefits of direct metal deposition (DMD), with specific focus on materials used in solid freeform processes, the value of uniform grain size and the metallic blending capabilities resulting from this new technology. SFF processes, such as DMD, can improve part strength and die life, and give users the ability to create unique, functionally graded materials. DMD produces a unique microstructure with consistent grain size and very little variation in hardness. This improves property strength and can significantly improve the life of costly, 'mission critical' die casting tools. Tool steel alloys made by the DMD process do not present challenges seen with cast steel processes, where alloy additions in the ingots tend to separate from the melt due to slow cooling. This separation affects final mold/ tool quality as properties like hardness cannot be consistently achieved. Instead of casting ingots, all alloy tool steel die casts are produced directly from tool steel in powder form. The rapid solidification of the process promotes almost no material separation. The alloy and carbides are finely distributed throughout the part. This results in isotropic properties and superior performance. DMD also allows for the use of pure copper and aluminum. By using these highly conductive and reflective materials, multi-metallic inserts can be fabricated for high-temperature, high-temperature and high-corrosion environments. This capability also lends itself well to the fabrication of functionally graded materials known as smart parts. Using DMD, powders can be blended to create alloys with unique physical properties, such as a tough inner core and high-strength, abrasion resistant outer surface. Lastly, DMD allows for the use of ceramics and metals to be fabricated in the same unit. DMD is the first production process to allow for the direct fabrication of these 'vermets', which have been employed in products that require unique thermal insulation, but also strength and ductility.

3:45 PM Y#2.6
SELECTIVE LASER SINTERING OF ZIRCONIA. Nicole Harlin, Seok-Min Park, David L. Boyer, J.J. Beaman, Jr., Mechanical Engineering Dept., Texas Materials Institute, The University of Texas at Austin, Austin, TX.

A combination of Selective Laser Sintering and colloidal infiltration has been used to fabricate zirconia monoliths for titanium casting. The mold material system was chosen for its low reactivity with molten titanium and thermal shock resistance. The base material, stabilized zirconia mixed with a copolymer binder, was pre-processed into granules and sintering into the desired green shape. A green density of the fired part could be increased to twice that of the green density. Hole sizes as small as 180 μm are possible in fully dense ceramic components.

4:15 PM Y#2.7
PROCESSING-STRUCTURE-PROPERTY RELATIONS OF POLYMER-POLYMER COMPOSITES FORMED BY CRYOGENIC MECHANICAL ALLOYING FOR SELECTIVE LASER SINTERING APPLICATIONS. Jeffrey P. Schalk, Julie P. Martin, Ronald G. Knder, Carlos T.A. Surielhe, Virginia Tech, Department of Materials Science and Engineering, Blacksburg, VA.

Cryogenic mechanical alloying (CMA) has been shown to be effective means for producing composite powders for selective laser sintering (SLS). Unlike composite particles made by the CMA process, both phases are continuous throughout the particles formed by CMA. The consolidation of these composite particles in SLS offers the possibility of forming parts with a co-continuous microstructure. In this research, the microstructure of intrinsically alloyed polymer composite powders for use in the SLS process is investigated using transmission electron microscopy. By varying the charge ratio and milling time of the CMA process, the phase domain size of the resulting composite powder can be manipulated and the physical and mechanical properties of the composite altered. This ongoing work explores the microstructural evolution as the composite powders are consolidated via SLS into macroscopic parts, as well as the relationships between microstructure and bulk properties.

4:30 PM Y#2.8
FABRICATION OF FUNCTIONAL SILICON NITRIDE COMPOSITES BY DIRECT PHOTO SHAPING. Susanna Ventura, Subhas Narang, Philippe Guerin, Susan Liu, SRI International, Menlo Park, CA; Doug Trat, AlliedSignal Ceramic Components, Torrance, CA; Pramod Khondaker, Rolls-Royce Allison, Indianapolis, IN.

SRI International has developed Direct Photo Shaping (DPS), a low-cost, multiple freeform fabrication process. This paper describes DPS fabrication of functional silicon nitride gas turbine engine components. Visible digital light projection is used as a maskless tool to selectively photodepose a photoactive ceramic dispersion. For each layer the projected image is changed according to the CAD data, describing the object being built and solidification takes place by photocuring of the exposed areas. Multiple layers are dispensed and photocured to fabricate the object of interest. The resulting green ceramic part is then fired and sintered into a fully dense ceramic part. Silicon nitride vanes for a Rolls-Royce Allison industrial gas turbine were fabricated from AlliedSignal AS800 silicon nitride. A high quality surface finish was achieved with minimal finishing. The vanes were burner-cig test under repeated thermal cycling with no damage to the component. Co-processed AS800 material was fixture-tested with excellent results. Hollow vanes of Rolls-Royce Allison's design are currently being built by DPS to facilitate cooling and allow a higher engine operating temperature. DPS has also been applied to the fabrication of alumina parts.

4:45 PM Y#2.9
REFRIGERATIVE STEREOLITHOGRAPHY WITH DIRECT MASKING FOR SUPPORT-FREE AND ACCURATE FABRICATION. Tamotsu Murakami, Akiya Kinumitaka, Noman Nakajima, Univ of Tokyo, Dept of Engineering Synthesis, Tokyo, JAPAN.

The authors propose a new method named "refrigerative stereolithography". In this process, a liquid photopolymer resin for a new layer is supplied, cooled, and then photopolymerized. Using a gel layer, instead of a liquid layer as in conventional stereolithography, leads to some advantages. First, so-called 'support' structures for isolated or overhanging shapes are unnecessary and distortion by photopolymerization might be reduced because the object being fabricated is buried and held by gel resin. Second, additional treatments for layers can easily be introduced. For example, excessive light exposure is needed in stereolithography to solidify the resin beyond one layer thickness, but this is unnecessary. Third, height direction accuracy can be improved because the top blocks the light exposure and avoids surplus growth only where it is unnecessary. Also, if we supply new gel resin layer and then draw a mask on its surface where photopolymerization is unnecessary, we can solidify a required shape using a lamp instead of liquid resin. Since we draw such a gel resin layer by layer, we name it "direct masking" method. The effectiveness of the refrig.
growth of ceramics from gas phase precursor mixtures containing dimethylethylamine/methane/oxygen and continuous wave/pulsed laser surface exposure, with high growth rate, in complex three-dimensional aluminum oxide structures, which, if required, can be modified with platinum using gas phase Pt(PPh)4. (2) Metal growth from surface adsorbed precursors and pulsed UV laser surface exposure with short pulses. (3) Growth of metal films from adsorbed precursors including W(CO)6 and focused Ga ion beam exposure yielding tungsten structures with down to sub-10 nm precision. Examples and applications will be presented.

9:45 AM Y3.4/V3.4
INK-JET DEPOSITION OF CERAMIC SLURRIES N. Reis, B. Derle, UMIST, Manchester Materials Science Centre, UNITED KINGDOM

We have successfully printed green ceramic objects from slurries of Al2O3 dispersed in a paraffin wax using a commercial inkjet printer designed for pattern making and other applications. Inorganic and organic particulate suspensions are more viscous than the fluids normally passed through inkjet heads. This may alter the response of the inkjet printing system to its process parameters, e.g. driving voltage and frequency. We have explored the influence of fluid properties on inkjet behaviour using CFD modelling and a parallel experimental study to determine the optimum inkjet printing conditions for ceramic suspensions.

10:00 AM Y3.5/V3.5

The direct patterned deposition by inkjet printing of polymers is an attractive option for forming patterned areas of thin polymer films with different light emitting properties (red, green, blue) for organic LED flip chip displays [1,2]. Conventional deposition techniques such as spin-coating lead to blanket films of a single color, and subsequent patterning of blanket films is difficult. For inkjet printing of polymer LEDs, one deposits a solvent droplet with the dissolved desired materials on an impermeable surface (e.g. indium tin oxide). The final profile of the deposited materials will critically depend on the redistribution of the dissolved molecules and polymers within the solvent droplet during the drying process. During drying, the liquid can flow within the droplet due to thermally-driven and convective-driven flows. In this paper, we examine the effect of such flows on the lateral distributions of organic dyes and small electron transport molecules in the final polymer film. When edge-pinning of the droplet occurs during drying, such flows can lead to a severe segregation of the dyes and molecules to the edge of the film, such that less than 1% of them remain in the active structure. This effect has been proven by photoluminescence and also by an X-ray microprobe. The effect can be overcome by reducing the driving force for the lateral segregation by reducing the deposition of the droplets, or by chemically bonding the molecules to a polymer backbone. Both methods have been demonstrated successfully in LED's practice, which will be discussed.


10:30 AM Y3.6/V3.6
CALCULATION OF HAMAKER CONSTANTS IN NON-AQUEOUS FLUID MEDIA. Nelson S. Bell and Duane Dimos, Sandia National Laboratories, Albuquerque, NM.

Colloidal processing of materials is a necessary component of many new techniques for freestand solids fabrication. The design of a solid-liquid system for creating an optimal dispersion must balance the advantages and disadvantages of material solubility, solvent viscosity and solvent boiling point/vapor pressure. Information on the effect of solvent choice on the van der Waals interaction between materials in not readily available for many systems other than water. This talk will discuss the calculation of Hamaker constants from spectroscopic information available in the literature, present Hamaker constants for several nonaqueous systems, and give some experimental results regarding the choice of a fluid system on solid freestand deposition for sample materials in the electronics industry.

10:45 AM Y3.7/V3.7
NANOTECHNICAL PRINTING: DIRECT PATTERNING OF NANO PARTICLE INKS TO FORM FUNCTIONAL LOGIC AND MICRO-ELECTRO-MECHANICAL SYSTEMS. Colin Baehr,
Sawyer Fuller, Eric Wilhelm, Sanil Griffith, Brent Ridley, Brian Hubert, Joseph Jacobson, MIT, Media Lab, Cambridge, MA.

Recently (Science, 286, 746, October 22, 1999) we demonstrated an all-inorganic field effect transistor fabricated by printing. This was accomplished by developing a novel nanoparticle ink material and led to the highest transistors which has yet been demonstrated by printing. The term nanotechnoeconomics refers to building functional structures (both logical and mechanical) from such nanoparticle inks. In this paper we report on recent progress towards directly patterning such inks to create both logic and machines (micro-

electro-mechanical).

11:45 AM Y3.10/V3.10

ELECTROSTATIC PRINTING, A VERSATILE MANUFACTURING PROCESS FOR THE ELECTRONICS INDUSTRIES: Robert H. Dzig, Electro Corporation, Denville, NJ.

Functional materials configured as liquid toners are printed on a variety of substrates for microelectronics manufacturing processes. These materials include metal toners, resistors, high 

dielectric toners, phosphors and ITO. The substrates printed upon include glass, bare and coated metal, polymeric film and even paper. A fixed composition electrostatic printing plate is used in most manufactur-
ing applications though traditional photo receptor plates can be used if electronic addressability is desired. Applications of electrostatic printing for electronic packaging products (printed wiring boards and field effect transistors) and of passive electronic components will be shown. Possible applications of toners to the manufacture of flat panel displays will be discussed. Results with a pure silver toner printed on both glass and paper will be reported. Examples of passive electronic components like resistors, capacitors, inductors and diodes that have been electrostatically printed with liquid toners will be shown.

SESSION V4: COMPOSITES AND CERAMICS

Chair: Paul Calvert and John W. Halloran Tuesday afternoon, April 25, 2000

1:30 PM Y4.1

MODELING AND OPTIMIZATION OF NOVEL ACTUATORS PRODUCED BY SOLID FREEFORM FABRICATION: Byun A. Cheung, Xinying Sun, Ted M. W. Chang, University of Delaware, Center for Composite Materials and Department of Mechanical Engineering, Newark, DE; Ahmad Safar, Stephen C. Danforth, Rutgers University, Department of Ceramic Science and Engineering and Center for Ceramic Research, Piscataway, NJ.

The ability of Solid Freeform Fabrication (SFF) to produce complex piezoelectric architectures has enabled the development of novel designs for PZT actuators. Recently, it has been shown that through the intelligent application of actuator geometry, polar direction, piezoelectric material direction, and electric field, the force and displacement output of a PZT actuator could be optimized [1]. The current investigation examines several piezoelectric actuator geometries, including dome and spiral-shape actuators and a telescoping-type actuator as shown in Figure 1. Using fine element analysis, parametric studies are performed to identify some key issues in the optimization of actuator performance. Parameters investigated include actuator height, thickness, length and piezoelectric property orientation. Results of the dome study indicate that an actuator having a tangentially alternating polar direction and applied electric field exhibits a much larger change of force compared to dome actuators using either a through-the-thickness or tangential polar direction. Analysis of spiral actuators indicates that the spiral geometry results in pronounced amplification displacement, which compared to the displacement of an actuator employing a piezoelectric strip. In summary, some remarks will be made on the optimal use of piezoelectric material properties and actuator geometry in actuator design.


1:45 PM Y4.2


Ceramic Stereolithography (CSL) is used to fabricate complex shape ceramic powder composites by laser photocuring a concentrated ceramic dispersion in photocuring solutions layer-by-layer. The main processing parameters in CSL such as layer thickness, resolution, wall spacing, and overcurve depend on the knowledge of light propagation in concentrated multiple scattering dispersion. In studies dealing with the processing of ceramic-filled organics, we investigated the depth of curing for model resin systems as a function of photoinitiator concentration. An optimal photoinitiator concentration that maximized the gel cure depth was observed. Two regimes were shown to exist in which the switch ratio was minimized or maximized. The study showed that photoinitiator plays a significant role in controlling the quality and performance of the formed gel network, with special regard to thickness of cured layer. This fundamental application to fields diverse as industrially cured coatings and dental fillings, and more generally, 3-dimensional fabrication techniques.
2:15 PM Y4.3
FREEFORM FABRICATION OF BONE IMPLANT MATERIALS
COMBINING A STRONG SUPPORT MATERIAL WITH A
BIODEGRADABLE COMPOSITE. Joe Walsh, Ranji Vaidyanathan,
Advanced Ceramics Research, Tucson, AZ; Shashan Sarangapani,
ICET Inc., Norwood, MA; Haripriya Chandru, Christian Haujano and
Paul Cullen, Department of Materials Science and Engineering,
University of Arizona, Tucson, AZ.

There has been long interest in biodegradable prosthetic bone
materials. An ideal material would be osteoconductive, promoting new
bone formation. It would also be tough and carry load until it is
wholly replaced by new bone. No existing material is wholly
satisfactory. Porous glasses tend to be brittle and have low strength in
stressed sites. Biodegradable polymers tend to lose strength long
time before they lose mass and are replaced. Freeforming methods
have been used to make porous implants from slowly-degradable
polymers. These methods are complicated with a large amount oxygen
hydroxyapatite blend. We will report on mechanical properties of
these implants at different stages of degradation in vitro, on studies of
degradation kinetics and on biocompatibility. In general, freeforming
methods offer a powerful route to forming such multi-component
biomedical materials.

2:30 PM Y4.4
PHOTOELECTRIC AND PIEZOELECTRIC SENSORS BY DIRECT
AND INDIRECT INKJET DEPOSITION. Gabriel T.M. Chu, Chris
J. Reilly, John W. Halloran, Department of Materials Science
and Engineering; Scott J. Holtzler, Department of Biomedical
Engineering, Syracuse University, Mechanical Engineering, University
of Michigan, Ann Arbor, MI.

Indirect inkjet printing of ceramics is done using wax molds from a
ceramic ink. A ceramic inkjet printing machine is used. Ceramic powders
are cast into the molds, followed by curing, binder burnout and sintering. Hydroxyapatite (HA)
prototypes for bone tissue scaffolds are built from Imaged-Based Design files, featuring an interior architecture of void passages. The results are compared to the HA scaffolds from the Indirect
Stereolithography method. Preliminary animal test results will be presented. Piezoelectric ceramic sensors are also built from PZT with the same technique. Direct inkjet printing of ceramic deposits
aqueous ceramic slurries in a drop-on-demand fashion. The high
temperature flow behavior, droplet formation and the drying behavior of
the slurry droplets are studied.

2:45 PM Y4.5
AUTOMATED FABRICATION OF CERAMIC ELECTRONIC
PACKAGES BY STEREO-PHOTOLITHOGRAPHY. Walter
Zeimet, T.K.T., Inc., Amityville, MD; J.H. Jiang, W. Schulte,
NYSCC, Alfred University, Alfred, NY; R.W. Rice, Consultant,
Springfield, VA.

Significant cost and time savings can be realized by applying
automated freeform fabrication techniques to the fabrication of
ceramic electronic packaging. The widely used thick film/screen
printing approach for ceramic packaging involves multiple separate
processing steps and is not suited to a large scale production.
Hydroxyapatite (HA) and calcium phosphate (TCP) have been
utilized for bone tissue scaffolds. The development of low and high
temperature co-fire ceramic systems (LTCC and HTCC) has
streamlined the firing process, but significant efficiencies remain in
constructing the green state package, such that prototyping of ceramic
packages is often very expensive with substantial lead times.
This paper describes an integrated approach which combines the
automated three-dimensional capabilities of stereolithography of
ceramics and metals with the high resolution and precision of advanced
photolithography systems. The process utilizes photocurable resins filled with sinterable ceramic and metal particles
which are applied layer-by-layer and photopolymerized to build up a
multilayer package. Materials development has focused on a
glass-ceramic bioceramic, a silver conductor and a boron nitride
dielectric. Resin rheology and photocuring characteristics, thermal
processing and sintered properties of the materials are described. A
breadboard processing system was constructed and the results of
fabricating test circuits are presented.

3:30 PM Y4.6
USING LAYERED MANUFACTURING TO CREATE TEXTURED
MICROSTRUCTURES IN Si3N4 CERAMICS. S. Rangarajan, B.L.
Harper A. Safari and S.C. Danforth, Rutgers University, Piscataway,
NJ; C. Gudziak, Allied Signal Research and Technology, Morristown,
NJ.

In recent years, seeding has been shown to be an effective method
to create designer microstructures in Si3N4, Al2O3 and PZT ceramics.

The objective of this research is to create micro and textured
Si3N4 parts using the Fusible Deposition of Ceramics (FDC) process.
The FDC process is a layered manufacturing technique which
involves hot extrusion of ceramic particle loaded binders through a
small orifice or nozzle. This technique is currently being developed
to fabricate high performance structural Si3N4-based components.
In order to create the textured microstructures, non-sintered Si3N4
seed particles are introduced into the FDC feedstock filaments and then
properly, the -Si3N4 seeds will align during extrusion and sintering.
The -Si3N4 seed particles orient along flow direction due to shear
stressinduced during feedstock filament extrusion and FDC
deposition. Texture develops in the microstructure during sintering if the
re-precipitated -Si3N4 grains preferentially on previously aligned
-Si3N4 seed particles. In this study, anisometric -Si3N4 seeds were
introduced into the starting o-Si3N4 powder (AlloyedSignal’s GS44
grade) at 2.5 and 10 vol% levels. The effects of the seeds [aspect ratio
~4] on the microstructure and resulting microstructure were evaluated.
Using a null-cavity resonance technique, the crystallographic cell of a single grain was determined.
Texture development was observed by x-ray diffraction. It is observed here that the seeds do align during filament
extrusion and a significant texture has been detected by x-ray diffraction.

3:45 PM Y4.7
ROBOSTRING AND MECHANICAL TESTING OF AQUEOUS
SiCERAMIC SHURBIES. G.P. He and D.A. Hirschfeld, New
Mexico Tech, Socorro, NM; J. Casamor III and J.N. Rauchek, Sandia
National Labs, Albuquerque, NM.

Aqueous slurries of silicon nitride were plasma sintered fabricated through a novel technique termed robostring. The process utilizes high solids loading slurries within 10% of green density while using no binder and less than 2 wt% organic in the form of polyethylene glycol.

The combined effects of polyethylene glycol, SiC, and Al2O3 powder loading exhibited a significant difference in the resulting microstructure. A single loading process through the layer-wise process, silicon nitride ceramic parts were fabricated without molds and subsequently fired to >100% theoretical density. Four point bending tests yielded an average strength of >725 MPa using ASTM standard C-1161.

Sandia is a multi-program laboratory operated by Sandia Corporation a Lockheed Martin company, for the U.S. Department of Energy under contract number DE-AC04-94AL66500.

4:00 PM Y4.8
µMOLD SHAPE DEPOSITION MANUFACTURING OF CERAMIC
PARTS. Seowun Nam, Pro-Oghin Lim, Jurgen Stampf, Peter B. Prinz,
Stanford University, Rapid Prototyping Lab, Stanford, CA.

µMold Shape Deposition Manufacturing (µMoldSDM) is being
developed to fabricate complex shaped parts in the millimeter and
submillimeter range out of a variety of materials. For this work we
present parts made out of ceramics (silicon nitride and alumina)
which have been molded (using gelcasting) into wax molds or
lithographically patterned photoresist molds. Due to the small size of the parts and conventional post-treatment processes to improve the mechanical properties (grinding etc.) of the sintered parts cannot be used. As sintered properties of these materials are therefore critical to the functionality of the parts fabricated for gas turbine engines. Processes involving the size and the geometry of the part
the molds are either manufactured by CNC machining of wax or by
deep lithography of photomasks (SU8). After casting and gelling the mold temperature increased. The green part can be treated in a conventional way. The mechanical and microstructural properties as well as the geometrical accuracy of the final parts are presented in this work.

4:15 PM Y4.9
AN ANALYSIS OF EXTRUSION IN THE FUSED DEPOSITION
OF CERAMICS PROCESS. S. Rangarajan, N. Venkateswaran, B.L.
Harper, A. Safari and S.C. Danforth, Rutgers University, Piscataway,
NJ.

The Fused Deposition of Ceramics (FDC) process is a solid freeform
manufacturing technique in which the material deposition process involves the hot extrusion of ceramic particle loaded binders through a
small orifice or nozzle. The fully automated FDC process requires
the plunger to be controlled. Filament with 55 vol. % of Allied Signal GS44 Si3N4 in RUB binder was the principal material for this study. Using a
capillary rheometer and dynamic strain rheometer, the steady state,
dynamic and transient rheological behavior of the material was
measured. Using the capillary extrusion process, the pressure drop
(AP) across dies of various geometries, including FDC nozzles, has
been measured. Based on these results, it was determined that the

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The multi-material layered manufacturing (LM) technology is under development in recent years. One of the main concerns of LM technologies is quality of the part, specifically, to keep the voids and defects within the acceptable limits. For multi-material LM, there are additional issues about materials matching within one part at the interface boundaries. Our ongoing research on multi-material layered manufacturing, the material-based build characteristics are defined. The hardware (called MU3H machine) is designed to accommodate this requirement. To fabricate high quality parts, and to make the development generic yet compatible with our hardware, an in-house virtual simulation system and an intelligent multi-material toolpath generation system have been developed. The multi-material toolpath generation software uses wireframe as input data. This system includes issues such as intelligent toolpath features for void elimination, and intelligent toolpath features for machine control. After the multi-material toolpath file generated by the in-house software, the existing graphical simulation as well as selected part fabrication experiments are being used to validate it. The virtual simulation utilizes physical roadmaps captured using video microscopy method. Problem of voids and defects, interface mismatch between adjacent materials are readily detected and quantified in the virtual simulation results. The parts have been fabricated using different material including wax, PZT, silicon nitride and 17-4PH stainless steel powder. Several objects with complex concave contours have been successfully simulated. The components such as metal molds, turbine blades, actuators, and fixtures have been designed, simulated, and fabricated. The properties of parts are being quantified in terms of quality and accuracy.

8:45 AM Y5.2 ROBOCASTING OF MULTI-MATERIAL SYSTEMS: MULLITE-ZIRCONIA. Hugh B Denham, John N Stuecker, Joseph Cesaroni III, Sandia National Labs, Albuquerque, NM.

Robocasting is a technique for fabrication of three-dimensional parts by a layerwise process. Aerogels slurries of ceramic powders were used to create unique parts consisting of more than one material. Zirconium oxide (zirconia) can be combined with mullite (alumino-silicate) to provide toughening. The thermal expansion mismatch between zirconia and mullite was used, along with discrete placement of each component provided by robocasting, yielding robust parts with surfaces in compression after sintering. Efforts toward adapting this multiple material system for robocasting, slurry development along with computer modeling support, will be discussed. Finally, the mechanical behavior of unique zirconia-mullite composites will be discussed, along with the potentials for graded structures and other multiple material systems.

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

9:00 AM Y5.3 FREEFORM FABRICATION OF MULTIMATERIAL STRUCTURES. Haripriya Chandran, Sridhar Kanchanitha and Paul Calvert, Arizona Materials Labs., Tucson AZ.

Layerwise processing methods allow different materials to be combined into a single monolithic solid. Two examples will be presented. Bars of epoxy resin, with a glass fiber screen reinforcement between one or more layers, have been made by extrusion freeform fabrication and the mechanical properties measured in layer testing. It is found that the fracture toughness is greatly increased if the reinforcing layer is weakly bonded into the composite and if multiple layers of reinforcement allow extensive pullout behind the crack front. The results will be compared with models for the fracture process. Glass ceramic bars have also been freeformed with cofired silver between layers. The morphology, conductivity and mechanical properties of these will also be reported. It is hoped that these results will shed light on the role of layered structures in toughening bone and mullite steel.

9:15 AM Y5.4 FREEFORM FABRICATION OF CERAMICS BY HOT MELT INK-JET PRINTING. B. Derby, N. Reis, Manchester Materials Science Centre, UMIST, Manchester, UNITED KINGDOM; K. Scurden, P.S. Grant, Department of Materials, University of Oxford, Oxford, UNITED KINGDOM; J.R.G. Evans Department of Mechanical Engineering, Queen Mary and Westfield College, London, UNITED KINGDOM.

Inkjet printing is a versatile freeform fabrication technique with a high spatial resolution. By suspending ceramic particles in low melting point organic materials and printing above the melting point, rapid cooling can impact on fine printing results in rapid layer growth. Current results from a collaborative program undertaken by NASA and wax inkjet-printing of structural ceramic components will be reported.
Simultaneous and key differences with related fabrication methods will be reviewed and key points for future research and development discussed.

9:45 AM Y5.5

PROCESS-PROPERTY-PERFORMANCE RELATIONSHIPS FOR FUSED DEPOSITION OF CERAMICS (FDC) FEEDSTOCK MATERIALS. N. Venkataraman, S. Ranganjan, B. Harper, M.J. Matthewson, A. Safari and S.C. Danforth, Department of Ceramic and Materials Engineering, Rutgers University, NJ.

Fused deposition of ceramics (FDC) is an extrusion based layered manufacturing process. It uses a high solids loaded (>50 vol. % ceramic or metal powder) thermoplastic binder in filament form as the feedstock material. The filament acts as both the piston driving the extrusion process and the feedstock material being deposited in the X-Y direction onto a Z-stage platform. The primary mode of failure of the filament during the FDC process is via bucking. This work has shown that the compressive modulus and the apparent viscosity of the feedstock materials determine their buckling behavior. A materials selection map has been developed, based on the ratio of filament elastic modulus to the apparent viscosity. In addition, the actual pressure needed to drive the extrusion through FDC nozzles has been determined as a function of nozzle geometry, flow rate and solids loading. A process map indicating the process performance of the feedstock materials has been developed based on the filament elastic modulus and the measured pressure drop. The paper will discuss the salient features of the materials selection map and the process map. In addition, efforts to understand the effect of processing variables such as solid loading, process conditions, part characteristics and agglomeration on the critical mechanical and rheological properties of the feedstock material will be discussed.

This work was sponsored under the ONR-MURI contract N00014-96-1-0176.

10:15 AM Y5.6

TAILORING SUSPENSION CHEMISTRY FOR FABRICATION OF DEFECT-FREE POWDER BEDS VIA SLURRY-BASED THREE-DIMENSIONAL PRINTING (3DP®). S.L. Morissette, S. Uhland, R. Holman, M. Cima, E. Sachs, Ceramics Processing Research Laboratory, Massachusetts Institute of Technology, Cambridge, MA.

Suspension composition determines several parameters critical to the slurry-based three-dimensional printing (3DP®) process, including slip casting rate, powder bed density and surface topography. Thus, fabrication of high quality, complex-shaped ceramic components via 3DP® requires careful control over slurry chemistry and printing conditions. Current efforts focus on investigating the influence of suspension chemistry on microstructure, dimensional accuracy and the resulting powder bed density, which in turn affects the microstructure of the deposited slurry and powder bed, surface topography, and defect generation. For example, recent studies have shown that structural and inter-layer defects (e.g., density gradients and slurry migration) resulting from differential slip casting (DSC) can be eliminated by varying binder content and solvent chemistry. The origin of inter-layer defects (e.g., air/bubble entrapment) generated at the slurry-powder bed and inter-layer remains unknown. This project will focus on investigating the effect of solvent chemistry and dispersant chemistry on the mechanical properties of 3DP® components and the approaches used to tailor printing suspensions for improved printing behavior.

10:45 AM Y5.8

GAZE PHASE SOLID FREEFORM FABRICATION. Harris L. Marcus, Shay Harrison, James E. Crocker, Linchao Sun, Eric Geiss and Leon Shaw, Institute of Materials Science, Metallurgy and Materials Engineering Department, Storrs, CT.

Localized CVD is the basis of two approaches to Solid Freeform Fabrication and related technologies. This paper will describe the recent efforts in selective area laser deposition (SALD) and SALD vapor infiltration (SALDVI). The SALD materials to be reported on include CVD of SiC, C, and Si3N4. The SALDVI process localized CVD into powders of SiC, Si3N4, Ni, and Mo. The resulting microstructure is inherently defined as a function of the processing parameters and the chemical interactions between the CVD materials and the powders.

11:15 AM Y5.9

EXPERIMENT AND MODELING ON PHYSICAL/CHEMICAL LIQUID DEPOSITION BASED SOLID FREEFORM FABRICATION. Gengnian J. Zheng and Zengyan He, Drexel University, Dept. of Mechanical Engineering and Mechanics, Philadelphia, PA.

Physical/Chemical Liquid Deposition Based Solid Freeform Fabrication (P/CLD-SFF) is a new rapid tooling (RT) technique proposed by the authors. It is based on the following experimental fact. When cold (room temperature) solution or liquid reactants is sprayed from a nozzle and contacted with a hot substrate, it can evaporate or decompose or react each other (if there are two or more reactants is sprayed at the same time). Then the solid or reactant will deposit on the substrate. By controlling the motion of the nozzle and the spray time, a desired 3-D shape of deposited material can be formed through layer by layer sintering. The proposed P/CLD-SFF includes Physical Liquid Deposition SFF (P-LD-SFF) and Chemical Liquid Deposition SFF (CLD-SFF). Although having different deposition principles, the two techniques have very similar technical processes and can be carried out with a same P/CLD-SFF system, only changing the starting materials. Compared with other RT techniques (Jukubec, Sanchez, and Marcus, 1997), P/CLD-SFF has higher accuracy and deposition rate, lower cost and investment. Especially, a wide range of materials such as salts, metals, alloys, ceramics and carbon materials can be deposited by P/CLD-SFF to form desired patterns or parts, and their chemical compositions, density and other properties can be controlled by designing suitable technical parameters.

Through a series of experiments, the authors found that the microstructure and strength of the deposited solid and the accuracy of the products all depend on the deposition temperature, liquid's flow rate and moving velocity of the nozzle. In order to calculate deposition rate, determine the above technical parameters and explain deposition phenomena, the authors proposed the heterogeneous nuclear and growth models on the separating process of solute from solvent. Based on these models, a deposition dynamics equation is deduced to describe the dynamic characteristics of P/LD-SFF. The calculation results of the models were compared with experiments and used to optimize technical parameters. Some deposition phenomena were analyzed and discussed based on these results.

11:40 AM Y5.10

PART RETRIEVAL IN THE SLURRY-BASED 3DP PROCESS. Scott A. Uhland, Richard K. Holman, Sherry L. Morissette, Michael J. Cima, Massachusetts Institute of Technology, Department of Materials Science and Engineering, Cambridge, MA. Emanuel M. Sachs, Massachusetts Institute of Technology, Department of Mechanical Engineering, Cambridge, MA.

Products which incorporate ceramic components frequently demand properties and shapes that challenge contemporary forming techniques. The Three-Dimensional Printing (3DP®) process has been modified to incorporate colloidal science for the fabrication of fine ceramic parts. Dielectric components were built using a sequential layering process of a ceramic powder bed followed by inkjet printing of a binder. An important processing step in 3DP® is removing the printed components from the powder bed. The part retrieval process plays a key role in the resulting shape and properties of the ceramic parts. Part retrieval is achieved through the redispersal of the powder bed. The addition of a redispersant to the slurry, e.g., polyethylene glycol increases the redispersal of the ceramic powder bed. Processing conditions, i.e., powder bed chemistry and the chemistry of the redispersing liquid, must be controlled throughout the process due to their strong influence on the redispersal behavior of the powder bed. The proposed technology has been used for the fabrication of dielectric RF components with extremely tight dimensional tolerances.

11:30 AM Y5.10

SILICON DIOXIDE NANOJETES PREPARED BY ANODIC ALUMINA AS TEMPLATES. Ming Zhang, Y. Bando, National Institute for Research in Inorganic Materials, Tsukuba, JAPAN.

Recently based on an ion ablation and catalytic chemical reaction methods, large-scale synthesis of silicon nanowires with ~40nm of diameter were prepared. Unfortunately, these techniques are difficult to be used for preparing silicon nanotubes. In this paper, the aligned silicon dioxide nanotubes with diameter of 30-40nm synthesized by the sol-gel template method is presented. This process involves the growth of nanotubes from the ordered nanochannel-array pores in anodic alumina. For a silica sol aged at room temperature and dried for 1 min., nanowires have been formed in a shorter period of aging time (2 days) and nanotubes connecting with solid nanofibers have been obtained in a longer aging time (30 days) The formation of nanotubes depends strongly on the temperature of the sol. For a short aging time (1 min.), the bamboo-like nanofibers were prepared when the sol was at high temperature (323K); however, the perfect nanotubes with the sharp wall were synthesized for the lower sol temperature (258K). The layered structure of the inside wall of nanotubes is. It is proved that the viscosity plays an important role on the morphology of nanotubes.
DIRECT FABRICATION OF BaTiO$_3$/SrTiO$_3$ LAYERED FILMS BY HYDROTHERMAL/ELECTROCHEMICAL METHOD IN A FLOW CELL
Tomoki Watanabe, Wojciech Suchanek, Naoki Kumagai and Masahiro Yoshimura, Tokyo Institute of Technology, Materials and Structures Laboratory, Yokohama, JAPAN.

Processing of thin films in the high-tech integrated devices has been dominated by physical vapor deposition (PVD) and chemical vapor deposition (CVD). In spite of many undeniable advantages of these processing routes, they usually require relatively high temperatures (above 500°C). Additionally, the PVD techniques require complicated equipment, such as high-vacuum systems, plasma systems, etc. The CVD processing utilizes typically gases, which are toxic, flammable, and/or corrosive, moreover some of them, such as silane, may even explode, therefore they present a serious hazard to humans. These features make the CVD and PVD environmentally stressed and expensive. However, it is also possible to fabricate the thin films directly from the solution under almost ambient conditions, for example by hydrothermal and/or electrochemical methods. Solution processing gives in many cases similar results than other processing such as CVD, PVD but consumes less energy, is environmentally friendly, requires simple equipment, and is inexpensive. We have proposed "Soft Solution Processing" for these methods. In this report, layered thin films in the BaTiO$_3$ – SrTiO$_3$ system have been fabricated by a hydrothermal/electrochemical method either in a closed autoclave or in a flow system using the titanium substrate and Ba$_2$ and Sr-dihydroxides or acetates as sources of titanium, barium, and strontium, respectively. The synthesis conditions (temperature in the range of 120-200°C, current density of 1-20mA/cm$^2$, flow rates of 1-50 cm$^3$/min, duration of 1-24 h) allowed an easy control of the microstructure of the titanate layers. The multilayered BaTiO$_3$ – SrTiO$_3$ thin films have been revealed by XRD, AFM, and XPS at various stages of their preparation. Based upon the experimental results, a growth mechanism of the BaTiO$_3$ – SrTiO$_3$ double layers has been proposed. We are also developing of in situ patterning of BaTiO$_3$ and SrTiO$_3$ films.